Aluminum Alloys: Fabrication, Characterization and Applications II
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DEVELOPMENT OF LOW COST, HIGH PERFORMANCE AlZn4.5Mg1 ALLOY 7020

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Abstract

This paper describes properties, processing, and performance of Al-Zn-Mg alloy 7020 for armor and commercial applications. Comparisons are made with alternative aluminum armors' chemistry, properties, levels of strength and ductility, weld properties, and resistance to stress and exfoliation corrosion. The advantages for development and optimization of alloy 7020 for vehicle armor or welded structures are identified to be: (1) low thermal sensitivity of the microstructure and mechanical properties to deleterious effects from reheat or solution-treatment and air-quench, (2) low Zn-Mg alloy and production costs, (3) adequate thick-plate strength and ductility for ballistic protection, and (4) high levels of weld strength and ductility in the natural or artificial aged condition. Concerns include: (1) optimizing thickness-dependent combinations of strength, toughness, and armor-threat-protection; and (2) optimizing processing and manufacturing techniques for mechanical properties and durability against stress and exfoliation corrosion.

Introduction

Humanitarian and military missions require logistical and combat vehicles capable of operation in largely undeveloped areas, on and off-road in areas of rough terrain. The hazards of these operations include the low-cost denial of area weapons, the landmine and improvised explosive device (IED) [1-3].

Effective protection for cargo transport, patrol vehicles, armored personnel carriers, and combat vehicles were developed in South Africa against mine blast threats and IEDs [1,2]. The light vehicle 4-6 passenger Cougar, retrofit on Land-Rover or Nissan chassis, was claimed to be the best land-mine protected vehicle of the Rhodesian war [1]. The heavy vehicle and 10-passenger capacity Buffel, built on a Unimog chassis, or the new monocoque-body 12-passenger Casspir proved among the most successful designs.

Casualty statistics [1, 2] proved that successful vehicle design elements should provide for long wheel bases, thin and tough ductile blast shields that deform but that do not become detached or displaced into the vehicle, high standoff height Vee-shaped hulls of ductile and tough mild steel that dissipate and deflect blast, hardened seating and safety belts, roll bars, over-pressure blow-off roof panels and fuel tanks.

Threats from mine and IED explosions include fragmentation, shock, overpressure, heat and combustion, and forces of acceleration and deceleration. The threats of mine casing fragments are similar to those of artillery. The ballistic protection, floor, and vehicle structure must resist deformation and stresses of the blast to avoid being torn apart, to form secondary fragments, and to avoid openings of doors or windows. Rapid deflection of floors caused by shock loading may cause fractures of feet, ankles, and legs. Acceleration and deceleration of the vehicle (see Figure 1 [3]) may rapidly subject the crew to incapacitating and lethal injuries of the neck and spine. The criterion of NASA for jet ejection seat force (23 g > 7 ms, g = 9.8 m/s

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14. ABSTRACT
This paper describes properties, processing, and performance of Al-Zn-Mg alloy 7020 for armor and commercial applications. Comparisons are made with alternative aluminum armors? chemistry, properties, levels of strength and ductility, weld properties, and resistance to stress and exfoliation corrosion. The advantages for development and optimization of alloy 7020 for vehicle armor or welded structures are identified to be: (1) low thermal sensitivity of the microstructure and mechanical properties to deleterious effects from reheat or solution-treatment and air-quench, (2) low Zn-Mg alloy and production costs, (3) adequate thick-plate strength and ductility for ballistic protection, and (4) high levels of weld strength and ductility in the natural or artificial aged condition. Concerns include: (1) optimizing thickness-dependent combinations of strength, toughness, and armor-threat-protection; and (2) optimizing processing and manufacturing techniques for mechanical properties and durability against stress and exfoliation corrosion.

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acceleration unit of earth gravity) has been used for estimation of back spinal injury [3].

Armor Materials for Protection against Blast and Projectiles

Materials used in the Cougar, Buffel, and Casspir Vee-hulls vehicles were "mild" steel resistant to the formation of fragments and splinters. These steels have advantages of high fracture toughness and ductility levels that resist crack initiation and propagation. Disadvantages of low-alloy steel include high density, and a temperature-sensitive yield stress [4] that increases the yield to tensile strength ratio and notch-sensitivity, lowering impact and fracture toughness and the ability for crack arrest under conditions of low temperatures and increased strain rate.

In comparison to steel [5] aluminum armor may provide weight savings to defeat the mine blast and small caliber armor piercing and fragment threats to mine resistant vehicles. With adequate combinations of strength, elongation, and fracture ductility (see Tables 1, 2), [6-14] aluminum armors, ranked 1 to 5 by yield strength (see Figure 2 [15]), provide excellent protection against fragment simulating projectiles (FSPs) beyond a critical thickness, shown by comparisons to V50 – areal density (AD) mean estimates (MEs) of 5083 and 7039 Al armors [9,13] and rolled homogeneous armor (RHA) steel [16], along with 95% confidence intervals (CIs) [17] for the 5083 MEs and single point future predictions (SPFPs). At equivalent weight, ballistic protection levels of aluminum versus armor piercing projectiles (AP) is largely dependent on yield strength and may be somewhat worse to better than average than RHA (see Figure 3 [15]). At low temperatures typical of aerospace (-88 ºC) or cryogenic environments (-196 ºC) strength, elongation, and K_{IC} fracture toughness of aluminum alloys typically increase over their room temperature values [18] suggesting improved resistance to ballistic perforation.

In addition to having the necessary properties of strength, elongation, and ductility for ballistics protection, candidate materials for mine resistant vehicles must resist structural failure by fracture initiation and propagation. Resistance to crack propagation by a full spectrum of deformation and fracture modes in rolled plates of aluminum alloys and under conditions of plane stress to plane strain has been characterized by fracture extension resistance (R-curve) properties determined by the dynamic tear (DT) test [19]. Use of aluminum materials to meet requirements for ballistic protection and structural integrity in mine-resistant vehicles will require careful selection of material properties to resist projectile and fragment threats and crack initiation and propagation. Vehicle design schemes to optimize protection levels include aluminum hulls, with aluminum of varied strengths, elongation, and toughness, and add-on or standoff armors to optimize protection from mine blast, fragments, or projectiles [20].

Low strength grades of the 5XXX series of aluminum have been shown to provide high resistance to crack extension and ability for fracture arrest [19]. Disadvantages of the 5XXX alloys are: (1) low levels of ballistic protection against AP projectiles (see Figure 3); (2) long-term exposure to elevated temperature in alloys with Mg content greater than 3% degrades resistance to stress corrosion [21]; (3) a typical loss of 50% of yield strength in fusion weld metal [22-25], (4) for thick plate the difficulty for cold work strengthening results in low strength and less efficient protection per weight [9, 11].

Aluminum 7020 Armor: Advantages and Concerns

The medium strength, Cu-free, low Mg-content alloy (<1.4 Mg) 7XXX Al-Zn-Mg alloys [24] including 7020-T651 (see Tables 3-4 and Figures 4-5) and 7005-T651 [18] (see Tables 1-2) have strength and ductility levels that typically provide improved resistance to penetration by fragments and armor piercing projectiles in comparison to 5083 aluminum and RHA (see Figures 2-3). With relatively high strength, the fracture arrest capability levels of these alloys as shown by 7005-T651 [19] may be of concern for thick sections. For high levels of protection versus projectiles, strength and ductility levels of alloy 7020-T651 can be maintained over 50 mm-

thickness [11] (see Figure 4 and Table 4).

During continuous heating, strengthening precipitates in Al-4.5Zn-1.2Mg alloy either completely dissolve above the solvus temperature of 350ºC or at lower temperatures undergo reversion, a quick decrease of precipitate volume fraction, and with times >100 seconds, a progressive slow coarsening stage that increases the volume fraction and precipitate size [6,26]. For vehicle-structural integrity, fusion welds of the Cu-free Al-Zn-Mg alloys typically regain 70% of their yield strength after 30 days of natural aging, and with artificial aging 100% of their original yield strength [23, 27] (see Table 5).

High levels of Zn makes aluminum solid solutions of Cu-free 7XXX alloys more electrochemically active and susceptible to galvanic corrosion [21]. The highest level of durability to SCC for 7020 is achieved by the T7 temper [10] (see Table 6). SCC resistance in Al-Zn-Mg alloys is achieved together by alloy chemistry and processing, product design, and manufacturing practice [6, 21, 24]. Following fusion welding, resistance to SCC [27] and exfoliation [28] is achieved by artificial aging (see Table 7).

The Cu-free 7XXX aluminum alloys contain low cost Zn and Mg alloy elements, and the alloys with Mg contents < 1.4 percent have low quench sensitivity that allows slow cooling rates and simple and economical heat treat processing by air-cooling. Air-cooling in these Al-Zn-Mg alloys provides optimal microstructures for improved resistance to stress corrosion cracking [6, 24, 27]. The alloy microstructures [26] obtained from duplex heat treatment to T7 tempers in 7XXX alloys provide improved levels of fracture toughness [6, 24, 27, 30], fracture ductility (see Figure 5), and protection versus FSP threats (see Figure 2).

Development Objectives for 7020

Objectives are to develop confidence in processing thin to thick plate 7020 aluminum armor for superior levels of weld strength and ductility, environmental durability, and ballistic protection to levels equal or superior to 5083 and 5059 aluminum armors. The approach shall include the determination of microstructure, properties, and performance of commercial plate in the T651 condition, and T6 and T7 conditions following MIG (metal inert gas) fusion welding and or artificial aging. Investigation of the MIG weld process shall include selections of filler metal alloy, travel speed and power. The quality, improvements, and performance of the parent metal and weldments shall be determined by microstructure, mechanical characterization, V50 performance and ballistic shock resistance, and determination of K_{ISCC} or critical levels of stress and time for the initiation of stress corrosion cracking. To obtain high levels of toughness similar to that for 7075-T7XX tempers (see Figure 5) and [30]), slow air cooling and overage or duplex high temperature temper treatments will be investigated for achievement of improved fracture ductility, crack arrest capability, and protection versus fragment threats and FSP projectiles.

Tables

Table 1. Aluminum armor and commercial alloy mechanical properties.

Alloy	0.2% Y.S. (MPa)	U.T.S. (MPa)	El. (%)	Data	Reference
7005-T651	290 (42)	370 (54)	15	typical	[6]
6061-T651	300 (44)	337 (49)	19	experiment	[15]
7018-T6751	300 (44)	360 (52)	12	typical	[7]
5083-H131	319 (46)	377 (55)	9.3	experiment	[8]
5059-H131	290 (42)	345 (50)	8	> 50.8mm, min.	[9]
5059-H131	296 (43)	393 (57)	7	12.7-50.8 mm, min.	[9]
7020-T7651	318 (46)	-	-	experiment	[10]
7020-T651	347 (50)	397 (58)	13	60.0 mm, cert	[11]
7020-T651	351 (51)	401 (58)	14	25.4 mm, cert.	[11]
2519-T87	423 (61)	465 (67)	12.4	experiment	[8, 12]
7039-T64	400 (58)	458 (66)	13.6	experiment	[8, 13]

Table 2. Aluminum Association chemical composition limits [14].

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	V	Zr	Date
6061	0.40 0.8	0.7	0.15 0.40	0.15	0.8 1.2	0.04 0.35	-	0.25	0.15	-	-	1954 USA
5083	0.40	0.40	0.10	0.40 1.0	4.0 4.9	0.05 0.25	-	0.25	0.15	-	-	1954 USA
5059	0.45	0.50	0.25	0.6 1.2	5.0 6.0	0.25	-	0.40 0.9	0.20	-	0.05 0.25	1999 Ger.
7005	0.35	0.40	0.10	0.2 0.70	1.0 1.8	0.06 0.20	-	4.0 5.0	0.01 0.06	-	0.08 0.20	1962 USA
7018	0.35	0.45	0.20	0.15 0.50	0.7 1.5	0.20	0.10	4.5 5.5	0.15	-	0.10 0.25	1978 UK
7020	0.35	0.40	0.20	0.05 0.50	1.0 1.4	0.10 0.35	-	4.0 5.0	Zr+Ti 0.25	-	0.08 0.20	1972 EAA
7039	0.30	0.40	0.10	0.10 0.40	2.3 3.3	0.15 0.25	-	3.5 4.5	0.1	-	-	1962 USA
2519	0.25	0.30	5.3 6.4	0.10 0.50	0.05 0.40	-	-	0.10	0.02 0.10	0.05 0.15	0.05 0.25	1985 USA
7017	0.35	0.45	0.20	0.05 0.50	2.0 3.0	0.35	0.10	4.0 5.2	0.15	-	0.10 0.25	1978 UK

Table 3. Certified chemical analysis of the commercial 7020-T651 alloys, weight-%, 14 plates among 12, 15, 20, 25, 30, 40, 50, 60, 80 mm-thick plates [11].

Chemistry	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Zr	Ti
Average	0.100	0.263	0.161	0.249	1.240	0.169	0.006	4.471	0.034	0.133
Std Dev	0.033	0.040	0.022	0.037	0.015	0.031	0.004	0.113	0.004	0.008

Table 4. Certified mechanical properties of commercial 7020-T651 plates [11].

Thickness (t)	0.2 % Y.S.	U.T.S.	Elong.	Hardness
(mm)	(MPa)	(MPa)	(%)	(HB)
12	360	408	16.8	-
15	361	409	13.7	-
20	351	403	14.0	116
25	351	401	13.9	-
30	351	401	15.0	116
40	340	393	14.0	117
50	348	397	12.8	-
60	347	397	13.0	115
80	320	370	13.1	-
Aver.,	351	401	14	116
Std. Dev.	8	6	1	1

Average and standard deviations: plate ≤ 60 mm thick

Table 5. GMAW mechanical properties and strength efficiencies.

Alloy	0.2%Y.S.	U.T.S.	El.(%)	Filler	Condition	Eff. (%)	Eff. (%)	Reference
	(MPa, ksi)	(MPa, ksi)				Y.S.	U.T.S	
5083-H131	319 (46)	377 (55)	9.3		base metal	-	-	[8]
	152 (22)	283 (41)	12.2		as-welded	48	75	[22,23,25]]
2519-T87	423 (61)	465 (67)	12.4		base metal	-	-	[8,22,25]
	209 (30)	301 (44)	4.4	2319	as-welded	49	65	[22,25]
7005-T6	290 (42)	370 (54)	15		base metal	-	-	[6,7,22]
	204 (30)	322 (47)	11		weld, nat. age 3 mo	70	87	[6,22]
7020-T651	352 (51)	390 (57)	18.5	5356	base metal	-	-	[27]
7020-T6	356	399	12.8	5356	1-P weld+art age	100	100	[27]
7020-T6	366	410	8.9	5356	2-P weld+art age	100	100	[27]

[27] 7020 = 1.6 mm sheet

Table 6. SCC stress intensity data for aluminum alloys, SL orientation, initiation.

Alloy	K_Q , K_{ISCC}	Environment	Ref.
2519-T87	21. 0	3.5% sol.	[8]
5083-H131	21. 3	3.5% sol.	[8]
5083-H131	10. 6	3.5% sol.	[8]
7017-T651	6. 7	3.5% sol.	[10]
7039-T64	6..3	3.5% sol.	[8]
7039-T64	4. 3	3.5% sol.	[8]
7020-T7651	28. 2	seawater	[10]
7018-T7651	38. 1	seawater	[10]
7017-T7651	6. 0	seawater	[10]

Note: method of reference [10] by crack propagation and arrest.

Table 7. Stress corrosion cracking, 5356 weld, mechanical test results.

Alloy/Filler	Test Condition	Stress (MPa)	Failures	Metallurgical Condition
7020-T6 / 5356	40 ºC, 80% RH	200	0/3	1-P weld + art age
	40ºC, 80% RH	160	2/3	2-P weld
	40 ºC, 80% RH	225	0/5	sol. treat. air quench, art.-age
	40ºC, 3% NaCl, pH4	225	0/3	480ºC sol. treat. air quench, art.-age
	40ºC, 3% NaCl, pH4	200	0	1-P weld + art. age, 1030 -1430 mV pot.
2519-T87 / 2319	3% NaCl, AI, C-ring, 90 hrs	138	4/4	Weld, bead, ST,

Notes: 7020 test data from [27]; 2519 test results from [8]; RH = relative humidity.

Figures

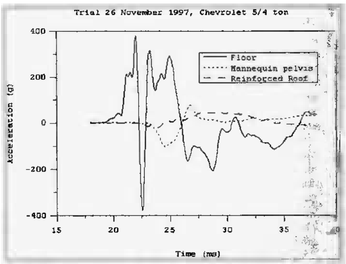

Figure 1. Time-acceleration effects, medium-sized blast mine equivalent to 7.5 kg TNT [3].

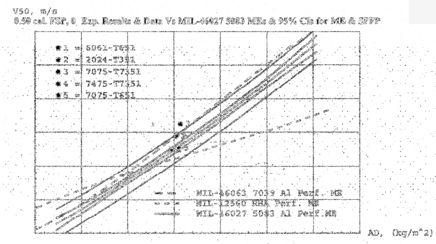

Figure 2. Commercial Al alloys protection V50 velocity by areal density (AD) versus 0.50 cal. FSP projectiles [15]. Comparisons to: 7039-T64 Al armor and rolled homogeneous armor (RHA) steel. V50 order 3, 4, 2, 5, 1.

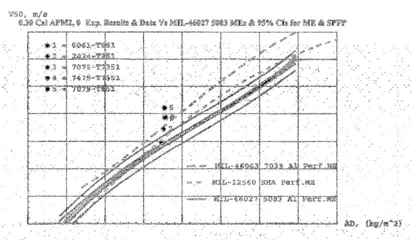

Figure 3. Commercial Al alloys protection V50 velocity level by areal density (AD) versus 0.30 cal.APM2 projectiles [15]. V50 order 5, 3, 4, 2, 1.

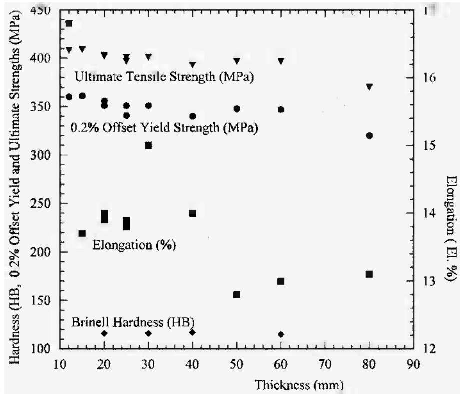

Figure 4. Mechanical properties and hardness of alloy 7020-T651 commercial plate, 12 mm to 80 mm-thick [11].

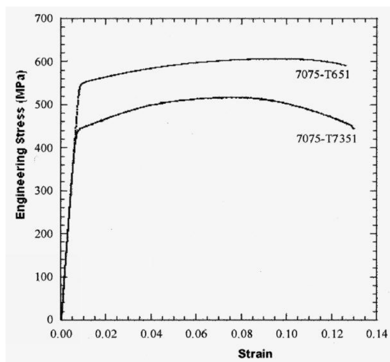

Figure 5. Engineering stress-strain plastic flow curves. Fracture ductility of T651 and T7351 temper [15].

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